OPEED: Optimal Energy-Efficient Neighbor Discovery Scheme in Opportunistic Networks

Dongmin Yang, Jongmin Shin, Jeongkyu Kim, and Geun-Hyung Kim

Abstract: **In opportunistic networks, it is difficult to predict when a node encounters others and how long it keeps in contact with another. Nodes continually attempt to explore neighbor nodes in the vicinity to transmit data. In battery-operated devices, this persistent exploration consumes a great deal of energy. In this paper, we propose an optimal energy-efficient neighbor discovery scheme (OPEED) that guarantees neighbor discovery within a delay bound. Through performance evaluation, we show that the OPEED scheme consumes 33%–83% less energy than other schemes.**

Index Terms: **Contact miss probability, delay bounded, energy-efficient, neighbor discovery, opportunistic networking.**

I. INTRODUCTION

OPPORTUNISTIC networking is an emerging technology with a wide range of potential applications (e.g., military, vehicular, rescue and medical service) [1]–[3]. Opportunistic networks are some of the most interesting evolutions in mobile ad-hoc networks (MANETs). In a practical MANET, links may be intermittently established due to a short transmission range and high user mobility. This is not the case in most previous works that have implicitly assumed that the network is connected and there is a contemporaneous end-to-end path between any two nodes [4], [5]. Before exchanging data, two nodes in physical contact must recognize each other through the operation of probing and responding [6]–[11]. If a node fails to recognize another node within its transmission range, it experiences extended delivery latency or a data delivery failure. One of the main challenges in opportunistic networking is finding such a neighbor in contact.

First, battery-operated devices cannot afford persistent probing. Therefore, a neighbor discovery scheme must be designed so that such devices can recognize each other with minimum energy consumption (EC). Second, for a symmetric neighbor discovery, the algorithm must provide minimum contact miss probability (CMP). Since all nodes in ad-hoc networking in general are considered to be homogeneous, they follow the same sequence of actions, called a symmetric manner. Note that as long as all nodes operate symmetrically, they may miss physical contact. Consider two nodes alternating between probing and listening modes; if their schedules happen to overlap exactly, they fail to recognize each other. This simple observation leads to the conclusion that there is no symmetric algorithm that guarantees zero CMP.

In this paper, we propose a symmetric neighbor discovery within a bounded delay D, where D is given as the desired discovery delay, the time difference between the beginning instant of physical contact, and the instant of discovering the contact. We determine the optimal tradeoff point between EC and CMP. If neighbor discovery succeeds within D, data exchange can be completed through this contact. D can either be given as a constant [8], [12] or probabilistically derived [6], [13], [14].

The remainder of this paper is organized as follows. We briefly discuss related works in Section II. Section III describes the system model and problem statement. Section IV presents CMP and the optimal probing schedule for a given duty cycle, and determines the optimal duty cycle. Section V compares the proposed scheme with other schemes. Finally, we conclude the paper in Section VI.

II. RELATED WORKS

Various studies [11], [15]–[17] have introduced the sleep mode, in which a radio is turned off when there is no data to forward. Similarly, an energy-saving scheme for opportunistic networking must be able to turn off the radio, thus setting a sleep mode, during non-contact time and be able to turn it on only for neighbor discovery and data exchange. Even if it is difficult to predict when the nodes will encounter each other and how long they will maintain contact, it is crucial to find such figures for successful data exchange and energy savings.

Wake-up patterns with a sleep mode have been proposed in [9], [10], [18]–[20], such that two nodes are awake for a certain period of time within a given interval. They assume that time is divided into fixed-width reference periods, called slots, and these slots are numbered 0, 1, $\cdots$. In wake-up schedule function (WSF) [9], WSF-(n_t, n_a, n_c), which can guarantee n_c opportunities for communication within n_t slots by waking up n_a slots out of n_t slots, is proposed. WSF-$(k^2+k+1, k+1, 1)$ was proved to provide a wake-up schedule only when k is a power of a prime. Asynchronous neighbor discovery and rendezvous protocol (DISCO) [10] picks up two prime numbers, p_1 and p_2. A node awakes in the slot where the slot number is divisible by p_1 or p_2. In quorum-based power-saving (QPS) [18], [19],

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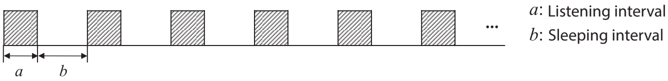

Fig. 1. Listening and sleeping modes.

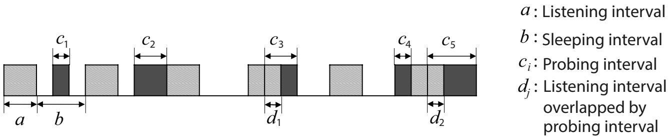

Fig. 2. Listening and probing modes.

one column and one row are picked in n^2 slots as a quorum set, where n is a positive integer. Nodes are in the wake-up state on the chosen slots. In adaptive, asynchronous rendezvous protocol (AARP) [20], given a prime number p, if the slot number and 0 are congruent modulo p or the slot number and 1 are congruent modulo $p+1$, a node turns on its radio, where the sequence length L is defined as $p\lfloor p/2 \rfloor$. WSF, DISCO, QPS, and AARP guarantee one overlapping slot within the k^2+k+1, $p_1 p_2$, n^2 and $p\lfloor p/2 \rfloor$ slots, respectively. They deal with two operation modes: sleep and wake-up. Note that they do not specify what to do in the wake-up mode. We believe that the wake-up mode must be elaborated depending on the action the node takes.

In this paper, we divide the wake-up mode into probing mode and listening mode. A node can be in one of three operation modes; probing, listening, or sleeping. To the best of our knowledge, we are the first to propose an asynchronous neighbor discovery within a bounded delay D taking into account all three modes. It is energy-optimal in the sense that OPEED minimizes the EC while providing minimum CMP.

III. SYSTEM MODEL AND PROBLEM STATEMENT

To illustrate the symmetric neighbor discovery process, we first consider a system where a node periodically listens to receive probing messages for interval a and then sleeps for interval b, as shown in Fig. 1 [21]. For numerical analysis, we define the duty cycle q as $a/(a+b)$. In addition, the node must send probing messages to detect encountering nodes. Therefore, three operation modes-listening, sleeping, and probing-are defined in our system model. All nodes operate in a symmetric manner. The probing intervals c_i $(i = 1,\cdots,M)$ may be placed arbitrarily, as shown in Fig. 2. Any listening intervals overlapped by probing intervals are no longer in listening mode and are denoted by d_j $(j = 1,\cdots,K)$.

Let E_P, E_L, and E_S $(E_P > E_L >> E_S)$ denote the energy consumed in the probing, listening, and sleeping modes, respectively. The total energy E_{total} consumed by a single node for the whole operation time T can be expressed as

$$E_{\text{total}} = E_P \sum_{i=1}^{M} c_i + E_L(Na - \sum_{j=1}^{K} d_j) + E_S(Nb - (\sum_{i=1}^{M} c_i - \sum_{j=1}^{K} d_j)). \qquad (1)$$

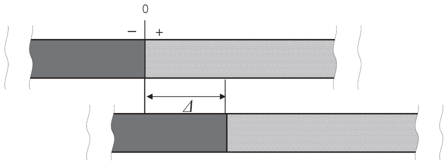

Fig. 3. Misalignment degree.

Without loss of generality, we assume $T = N(a+b)$, where N is the number of listening (or sleeping) intervals. M and K are the number of probing intervals and listening intervals overlapped by probing intervals in T, respectively. The key notations used in this paper are shown in Table 1.

To achieve neighbor discovery within given D, a node must perform probing at least once within every D period $(M \geq N)$. If a node does not listen to a probing message for an interval greater than δ, which is the minimum listening interval required to recognize a probing message, two nodes in physical contact may fail to recognize each other. For numerical analysis, we define P_{miss} as the probability that two nodes in physical contact may fail to recognize each other within D.

In this study, we investigate how to schedule probing, listening, and sleeping intervals such that any node can detect physical contact with a neighbor node within D while both E_{total} and P_{miss} are minimized. The problem can be stated as follows.

$$\begin{aligned} &\text{minimize (over } a, b, c_i) \; P_{\text{miss}} \text{ and } E_{\text{total}} \\ &\text{subject to } \; c_i > 0, i = 1,\cdots,M \\ &\qquad\qquad d_j \geq 0, j, = 1,\cdots,K \\ &\qquad\qquad D > 0. \end{aligned} \qquad (2)$$

IV. OPEED SCHEDULING

To achieve a solution for the problem, two observations are found and used as clues to derive OPEED. First, we suggest a probing interval c_i for minimum CMP in subsection IV-A. Then, we derive the optimal listening interval a and sleeping interval b to minimize EC in subsections IV-B and IV-C, respectively.

A. Deriving the Probing Interval for Minimum CMP, c

First, when nodes of period D operate symmetrically, we derive the lower bound on P_{miss}. Next, we determine a probing interval for minimum P_{miss}.

Since nodes follow the same sequence of actions, it is possible for them to miss probing messages if their actions are perfectly synchronized. We define the misalignment degree as the extent to which one node is shifted from the other node from the exactly aligned instant. This is denoted as Δ. In Fig. 3, if $-\delta < \Delta < \delta$, they cannot recognize each other. This leads to the conclusion that if a schedule is in period D, the lower bound on P_{miss} is $2\delta/D$.

To determine a probing interval, we introduce two observations:

1. A probing interval must be longer than a sleeping interval $(c_i > b)$.
2. A probing interval must be adjacent to a listening interval.

Table 1. Notations in the system model.

Notation	Description
D	Given delay bound
T	Whole operation time
a	Listening interval
b	Sleeping interval
c_i	Probing interval
d_i	Overlapped listening interval with probing interval
q	Duty cycle $a/(a+b)$ (ratio of listening interval)
δ	The minimum listening interval required to recognize a probing message
N	The number of listening and sleeping interval pairs in T
M	The number of probing intervals in T
K	The number of listening intervals overlapped by probing intervals in T
E_{total}	Total energy consumed on a node in T
P_{miss}	Contact miss probability (CMP)
Δ	Misalignment degree

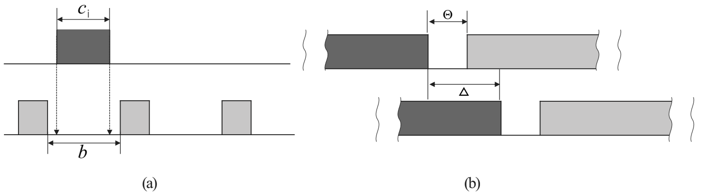

Fig. 4. Two observations: (a) Observation 1 and (b) observation 2.

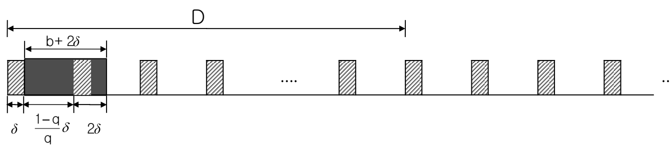

Fig. 6. Optimal probing and listening schedule for given duty cycle q.

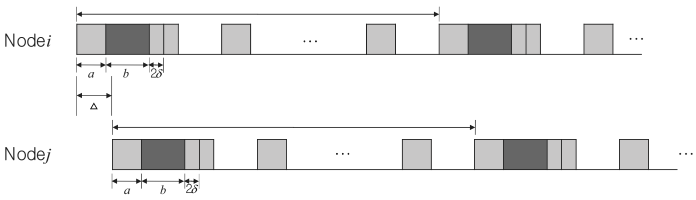

Fig. 5. Asynchronous interaction of two approaching nodes.

In Fig. 4(a), if $c_i \leq b$, two nodes fail to recognize each other whenever the probing interval of one node is placed on the sleeping intervals of the other node. Therefore, c_i must be longer than b. We denote the length of a sleeping interval between a probing interval and a listening interval by Θ. In Fig. 4(b), when $-(\delta+\Theta) < \Delta < (\delta+\Theta)$, they miss contact. We know that $\Theta = 0$ when a probing interval is adjacent to a listening interval.

From the two observations, a probing interval is longer than a sleeping interval and is followed by a listening interval, as shown in Fig. 5. The starting instant of a period on one node is uniformly distributed over the period of the other node when it is enclosed. P_{miss}, a function of c_i ($b < c_i < D - a$), can be obtained by determining whether a probing message of $Node\ j$ can be recognized by $Node\ i$ for $0 < \Delta < D$. For $b < c_i < D - a$, P_{miss} is derived as

$$P_{\text{miss}} = \begin{cases} \frac{2\delta}{D} + \frac{2\delta-(c_i-b)}{D}N & \text{, if } b < c_i < b+\delta \\ \frac{2\delta}{D} & \text{, if } b+2\delta \leq c_i < D-a. \end{cases} \quad (3)$$

Therefore, in order to achieve the minimum P_{miss} ($= 2\delta/D$), the probing interval is longer than $b + 2\delta$ ($c_i \geq b + 2\delta$). To minimize EC, the probing interval c_i must be equal to $b + 2\delta$, which is denoted by c.

B. Determining the Listening Interval for Minimum EC, a

In this section, we derive a listening interval for minimum EC. Equation (1) and the probing interval derived in the previous section lead to $K = M$, $T = MD$, and $c = b + 2\delta$. Then, the total energy is expressed by

$$\begin{aligned} E_{\text{total}} &= E_P \sum_{i=1}^{M}(b+2\delta) + E_L(Na - \sum_{i=1}^{M}\delta) \\ &\quad + E_S(Nb - \sum_{i=1}^{M}(b+\delta)) \\ &= \frac{T^2(1-q)(E_P-E_S)}{ND} \\ &\quad + \frac{T(2E_P-E_L-E_S)\delta}{D} \\ &\quad + T(E_L q + E_S(1-q)) \end{aligned} \quad (4)$$

using $b = (1-q)T/N$.

In (4), E_{total} is a function of N and q, which are independent. The duty cycle q will be discussed in depth in subsection IV-C. For the time being, suppose that q is constant. The minimum bound for E_{total} can be determined when N is maximized. To maximize N, every listening interval a is set to δ, then $b =$

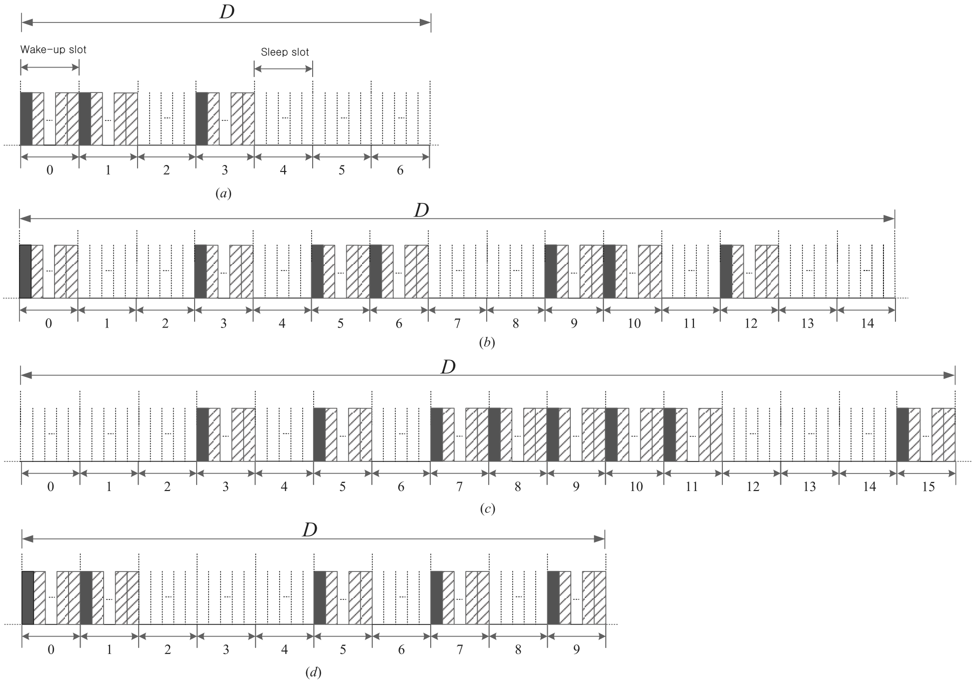

Fig. 9. Wake-up schedules of: (a) WSF-$(7, 3, 1)$, (b) DISCO at $p_1 = 3$ and $p_2 = 5$, (c) QPS at $n = 4$, and (d) AARP at $p = 5$.

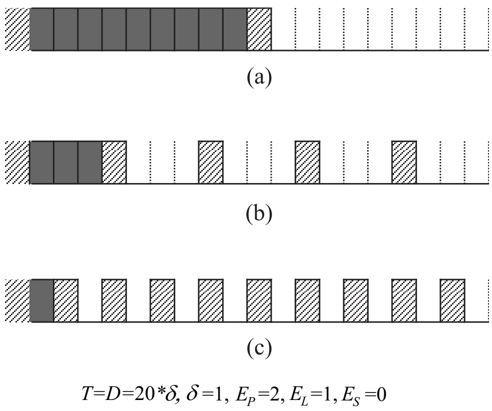

Fig. 7. How to obtain the optimal duty cycle: (a) $(q) = 0.1 \rightarrow E_{\text{total}} = 2 + 2 \cdot 9 = 20$, (b) $(q) = 0.25 \rightarrow E_{\text{total}} = 5 + 2 \cdot 3 = 11$, and (c) $(q) = 0.5 \rightarrow E_{\text{total}} = 10 + 2 \cdot 1 = 12$.

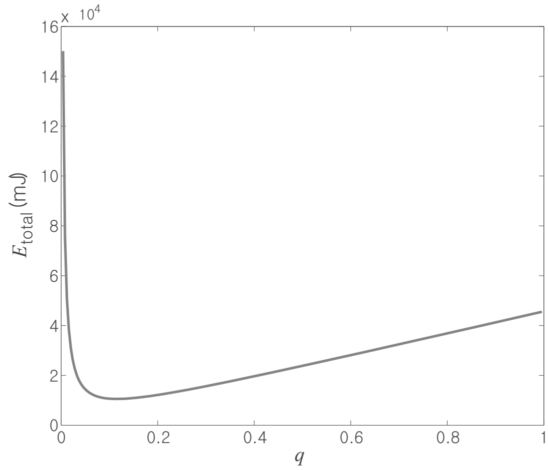

Fig. 8. Determining the optimal duty cycle.

$1 - q\delta/q$, as shown in Fig. 6. As a result, an achievable EC is

$$E_{\text{total}}^{\min} = \frac{T\delta\{(E_P - E_S)(1-q) + q(2E_P - E_L - E_S)\}}{Dq} + T(E_L q + E_S(1-q)) \quad (5)$$

using $N = Tq/\delta$.

C. Determining the Sleeping Interval for Minimum EC, b

In the previous sections, we determined a listening interval a $(= \delta)$ and derived a probing interval c $(= b + 2\delta)$ and a sleeping interval b $(= 1 - q\delta/q)$. Two variables c and b are dependent on duty cycle q. In this section, we introduce a method to determine the optimal duty cycle for a node. Fig. 7 illustrates how the optimal duty cycle can be obtained. When the duty cycle is small, the listening energy decreases, but the probing energy increases (see Fig. 7(a)). In contrast, when the duty cycle is large, the listening energy increases, but the probing energy decreases (see Figs. 7(b) and 7(c)).

Therefore, we can obtain the optimal value of a duty cycle by setting the derivative of $E_{\text{total}}^{\min}$ with respect to q to zero:

$$E_{\text{total}}^{\min'} = T[(E_L - E_S) - \frac{(E_P - E_S)\delta}{Dq^2}]. \quad (6)$$

The minimum value of $E_{\text{total}}^{\min}$ is proved to exist by using the second derivative test:

$$E_{\text{total}}^{\min''} = \frac{2(E_P - E_S)\delta T}{Dq^3} > 0. \quad (7)$$

Table 2. EC and CMP.

	Normalized energy consumption	Miss probability
WSF	$E_{\mathrm{WSF}}=\frac{(k+1)E_P+(n_s-1)(k+1)E_L+n_s k^2 E_S}{n_s(k^2+k+1)E_P}$	$P_{\mathrm{WSF}}=\frac{2(k^2+k+1)\delta}{D}=\frac{2}{n_s}$
DISCO	$E_{\mathrm{DISCO}}=\frac{2(p_1+p_2)E_P+(n_s-2)(p_1+p_2)E_L+n_s(p_1p_2-p_1-p_2)E_S}{n_s p_1 p_2 E_P}$	$P_{\mathrm{DISCO}}=\frac{2p_1p_2\delta}{D}=\frac{2}{n_s}$
QPS	$E_{\mathrm{QPS}}=\frac{(2p-1)E_P+(n_s-1)(2p-1)E_L+n_s(p^2-2p+1)E_S}{n_s p^2 E_P}$	$P_{\mathrm{QPS}}=\frac{2p^2\delta}{D}=\frac{2}{n_s}$
AARP	$E_{\mathrm{AARP}}=\frac{(p-1)E_P+(n_s-1)(p-1)E_L+n_s(p\lfloor p/2\rfloor-p+1)E_S}{n_s p\lfloor p/2\rfloor E_P}$	$P_{\mathrm{AARP}}=\frac{2p\lfloor p/2\rfloor\delta}{D}=\frac{2}{n_s}$
OPEED	$E_{\mathrm{OPEED}}=\frac{\{E_P(\frac{(1-q_{\mathrm{opt}})\delta}{q_{\mathrm{opt}}}+2\delta)-E_L\delta-E_S(\frac{(1-q_{\mathrm{opt}})\delta}{q_{\mathrm{opt}}}+\delta)+D(E_L q_{\mathrm{opt}}+E_S(1-q_{\mathrm{opt}}))\}}{(E_P D)}$	$P_{\mathrm{OPEED}}=\frac{2\delta}{D}$

Hence, the optimal duty cycle is determined by

$$q_{\mathrm{opt}}=\sqrt{\frac{(E_P-E_S)\delta}{(E_L-E_S)D}}. \quad (8)$$

From (8), the sleeping interval b is $1-q_{\mathrm{opt}}\delta/q_{\mathrm{opt}}$.

Fig. 8 shows that the optimal duty cycle (0.115499) is determined at the point where $E^{\min}_{\mathrm{total}}$ (= $1.05541\times10^4\ mJ$) is minimal. Each variable is set to $T=10^6\times\delta$ ms, $D=10^2\times\delta$ ms, $\delta=1$ ms, $E_L=45$ mW, $E_S=0.09$ mW, and $E_P=60$ mW.

V. PERFORMANCE EVALUATION

We compared OPEED with WSF [9], DISCO [10], QPS [18], [19], and AARP [20], which are all symmetric neighbor discovery schemes. We assume that a node probes at the start of each wake-up slot and listens for the remainder of the wake-up slot [9]. Fig. 9 illustrates the wake-up schedules for WSF, DISCO, QPS, and AARP. Without loss of generality, the size of a slot is a multiple of δ, $n_s\delta$, where n_s, which depends on the system, is assumed to be 10.

We conducted a numerical analysis to evaluate the performance of the algorithms in which two metrics were considered-the EC and the CMP. EC is normalized by dividing total EC during D by DE_P, which is the amount of energy consumed when a node keeps probing during D. The CMP is defined as the ratio of the number of contacts not successfully discovered to the total number of contacts. Normalized ECs are denoted by E_{WSF}, E_{DISCO}, E_{QPS}, E_{AARP}, and E_{OPEED}, respectively. The CMPs are denoted by P_{WSF}, P_{DISCO}, P_{QPS}, P_{AARP}, and P_{OPEED}, respectively. We assume that D is given in ms and δ is 1 ms. Power consumption for probing, listening, and sleeping are 60 mW, 45 mW, and 0.09 mW, respectively [22]. The normalized ECs and CMPs can be expressed as shown in Table 2.

Fig. 10 shows the normalized EC during D as the number of tags is increased. The results show that OPEED clearly achieves lower energy consumption compared to WSF, DISCO and AARP. Fig. 11 depicts the CMP. Table 2 shows that $P_{\mathrm{WSF}}=P_{\mathrm{DISCO}}=P_{\mathrm{QPS}}=P_{\mathrm{AARP}}\gg P_{\mathrm{OPEED}}$. When $n_s=10$, while the CMP of other schemes is a constant of 0.2, the CMP of OPEED decreases as D increases. OPEED always has the lowest probability, which is a function of D. As shown in Figs. 10 and 11, OPEED outperforms other schemes in terms of the EC and CMP. For $n_s\neq10$, the shapes of the EC and CMP graphs are retained.

WSF, DISCO, QPS, and AARP provide the wake-up schedules for only a few delay bounds in $0<D<1400$. For example, WSF only gives the wake-up schedules for the delay bounds

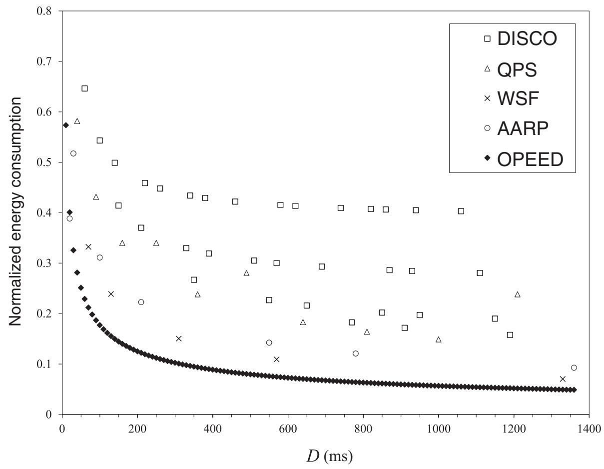

Fig. 10. Normalized ECs of WSF, DISCO, QPS, AARP, and OPEED.

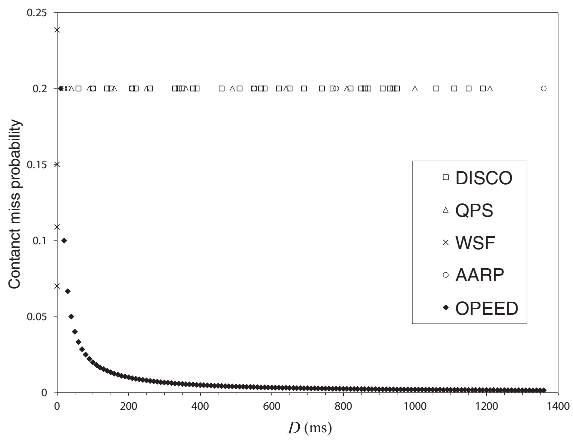

Fig. 11. Contact miss probability (CMP) of WSF, DISCO, QPS, AARP, and OPEED.

of 70, 130, 310, 570, and 1330 ms in $0<D<1400$. This is because WSF has a theoretical basis of prime numbers, as do DISCO and AARP. QPS is based on the *quorum* concept, where the number of slots for the wake-up schedule is the square of an integer. Therefore, QPS also restrictively provides the wake-up schedules. In contrast, OPEED always provides the wake-up schedules for any given delay bound D.

VI. CONCLUSION

In opportunistic networking, nodes must continuously probe their neighborhood in order not to miss an opportunity for data delivery. This persistent probing imposes a significant burden on battery-operated devices. Therefore, we proposed the neighbor discovery scheme, which guarantees a bounded delay providing minimum EC and CMP. Through performance comparison, we showed that OPEED achieves a significant energy-efficiency and provides excellent successful neighbor discovery. In the near future, to validate the effectiveness of OPEED, we plan to implement OPEED on universal software radio peripheral modules or other hardware platforms.

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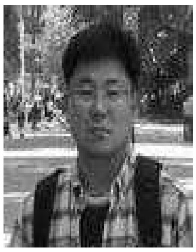

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